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STUDIES OF ERROR IN TEMPERATURE MEASUREMENT WITH THERMISTORS IN THE RANGE BETWEEN CONTINUAL AND FREE-MOLECULE FLOWS

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Translation of "Issledovaniya Poreshnosti Izmereniy Temperatury s Pomoshch'yu Termistorov v Diapazone Mezhdu Kontinual'nym i Svoboono Melekulyarnth Techeniyami", Investigation of the Earth's Upper Atmosphere, Gidrometeoizdat, 1978, PP 256-262

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16. Abstract

In the present paper, simple interpolation formulas for the temperature recovery factor and the heat-transfer coefficient (Nusself number) are derived for a sphere in the intermediate flow region. The results apply to bead thermistors intended for temperature measurements from rockets.

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When a thermometer is placed in the atmosphere, the temperature sensor does not pick up the environmental temperature in most cases. The magnitude of the discrepancy, which is the measurement error, is due to heat transfer between the sensor and the rapidly flowing air. * 256/

The magnitude of the error is written according to reference 1 in the form

$$mc\frac{dT}{dt} = \alpha F\left(T_0 - T - r\frac{v^2}{2c_p}\right)$$

or

$$T_0 - T = \frac{mc}{\alpha F}\frac{dT}{dt} - r\frac{v^2}{2c_p},$$

i.e., the error amounts to the error due to inertia and the error due to dynamic heating. Here m is the mass, c is the specific heat capacity per unit volume of the sensor, F is the surface, T is the temperature of the sensor, T_0 is the air temperature, t is time, v is the velocity of the sensing element in relation to the velocity of the air, c_p is the specific heat capacity per unit volume of the air at constant pressure, α is the heat-transfer coefficient, and r is the temperature recovery coefficient.

We will use dimensionless parameters:

Nusselt

$$\mathrm{Nu} = \frac{\alpha}{\lambda} D,$$

where λ is the thermal conductivity of the air and D is the characteristic size of the sensor

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$$\mathrm{St} = \mathrm{Nu}/\mathrm{Re}\,\mathrm{Pr},$$

where $\mathrm{Re} = \frac{\rho v D}{\eta}$ is the Reynolds number, $\mathrm{Pr} = \frac{c_p \eta}{\lambda}$ is the Prandtl number, ρ is the air density, and η is the coefficient of dynamic viscosity.

Then Nu and r are the determining parameters of the errors of inertia and dynamic heating of the temperature sensor, and they are a function of the shape of the sensor and the relative velocity and density of the air. Theories exist that enable one to examine Nu and r in continual and free-molecule flows. There is, however, no systematic theory for the region of flow between these two regimes. For that reason, this paper attempts to physically interpolate the heat transfer between these fundamental flow regimes. Such an approach is

* Numbers in margin indicate pagination of foreign text.

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dictated by the practice of rocket measurements, since the sensors pass through all the flow regimes in flight.

The sphere, which can serve as a model of the bead thermistor, is a convenient shape for the calculation.

Stokes' law is known for a sphere traveling in a continual medium. In a continuum, it is assumed that the medium immediately next to the streamlined body does not move, but adheres to it. It is also known that when the density decreases, the fluid or gas begins to slip along the solid surface. For that reason, the phenomenon is called slip flow. One of the basic ideas of this paper is to introduce this slippage into the Stokes' equation for a flow past a sphere, after which the equation of motion is solved. The field of velocity obtained is introduced into the energy balance, which for these purposes was divided into thermal conductivity in the boundary layer, heat of compression, and dissipation of friction. In this case, for heat transfer parameters, we obtain

$$\mathrm{Nu} = 2,$$

$$r = \mathrm{Pr}\left(1 - 2m \quad \frac{8}{3} m^2\right),$$

where m is the slip factor introduced into the calculation of the relationship

$$V_\theta = - mV_0 \sin\theta \qquad \text{when} \qquad R = R_k,$$

where θ and R are the coordinates of the sphere, R_k is the radius of the sphere, V_θ is the velocity component, and V_0 is the velocity of the undisturbed flow.

In fact, m represents the relationship between the velocity at the pole of the sphere and the undisturbed velocity. With full slippage, m = 1 and the continuum disappears completely; with an undisturbed continuum, m = 0. Thus, m is a function of the density of the flowing medium.

We accept the notion that in a free-molecule flow past a sphere, the velocity distribution of the molecules is Maxwellian. The solution given in reference 2 is well known for the heat transfer. The mathematical expressions for Nu and r relative to the sphere are so complex that they are impractical for the introduction of disturbance values. The second basic idea of paper amounts to determining the heat transfer parameters of a gas that has a single heat-transfer coefficient for all molecules and comparing the findings with those in reference 2. 258/

If the number of molecules in one cubic centimeter is known and is equal to n_0, then

$$n_1 = \frac{n_0}{2} \sin\mu \left(C_0 \cos\mu - V_0 \cos\vartheta\right)$$

/2/

represents the flow of molecules flying in the direction and hitting that sector of the sphere's surface that is characterized by the angle ϑ relative to the direction of the flow velocity vector. The translational energy of one molecule flying in that direction will be equal to

$$e_{\vartheta\mu} = \frac{M}{2}(V_0^2 + 2C_0V_0\cos\vartheta\cos\mu + C_0^2),$$

where C_0 is the heat-transfer coefficient of the molecules, C_0^2 is the mean quadratic heat-transfer coefficient, V_0 is the velocity of the sphere relative to the air, and M is the mass of one molecule of air.

In addition, the balance includes the translational energy after impact and the rotational energy before and after impact.

After integrating for μ, we get the energy balance of the surface element with an orientation ϑ from the energy balance n_μ of the molecules. The integration assumes that only below the limiting angle μ_g do the molecules reach the surface element. Corresponding with equation (6), this limiting angle is defined as

$$\cos\mu_g = -\frac{V_0'}{C_0}\cos\vartheta.$$

By further integrating the sphere's surface for all elements, i.e., for ϑ, we get the total heat balance of the sphere in a free-molecule flow. In order to get the Stanton number, the number of molecules are also integrated and then divided by the energy of one molecule; to calculate the coefficient of temperature recovery, the energy is inserted into the integration. The result of the integration presents rational functions of the molecular Mach number S.

The most time-consuming part of the work is testing the various mean values of the velocity C_0 and the kinetic energy $\frac{M}{2}(C_0^2)$. The best match with the results presented in reference 2 was obtained when we assumed that both the mass velocity and the energy of all the molecules are mean values of the quantities distributed according to Maxwellian law. The study of the various methods of averaging molecular magnitudes was undertaken in reference 3.

As a result of the above operations, for the free-molecule flow we get

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$$\mathrm{Nu} = \frac{3}{32}\frac{1}{\mathrm{Kn}}\left(1 + \frac{16}{27\pi}S^2\right)\frac{14\mathrm{Pr}-4}{5}, \quad S < 1{,}33,$$

$$\mathrm{Nu} = \frac{\sqrt{\pi}}{8}\frac{S}{\mathrm{Kn}}\left(1 + \frac{3\pi}{16}\frac{1}{S^2}\right)\frac{14\mathrm{Pr}-4}{5}, \quad S > 1{,}33;$$

$$r = \left(2 \quad \frac{2}{3} \frac{1 - \frac{16}{45\pi} S^2}{1 + \frac{16}{27\pi} S^2} \right) \frac{5Pr}{14Pr - 4}, \quad S \quad 1{,}33,$$

$$r = \left(2 + 2 \frac{1 - \frac{9\pi}{80} \frac{1}{S^2}}{+ \frac{16}{3\pi} S^2} \right) \frac{5Pr}{14Pr - 4}, \quad S \geqslant 1{,}33.$$

By way of example, Figure 1 presents a comparison of approximations with precise results (from reference 2) for the temperature recovery coefficient.

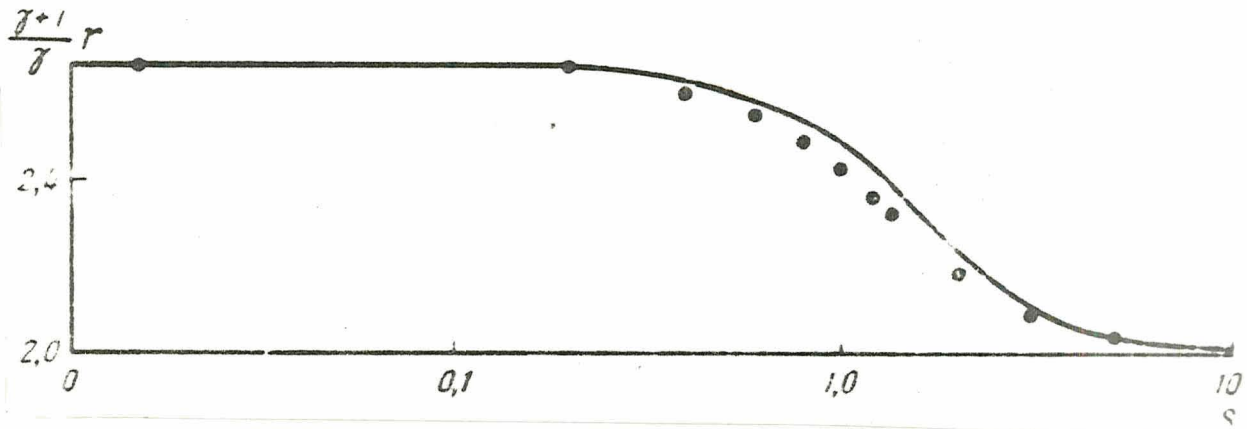

Figure 1. Temperature recovery coefficient r as a function of the molecular Mach number S in formula (10) $\frac{\gamma}{\gamma-1} = \frac{5Pr}{14Pr-4}$. The points represent Oppenheim values.

The insufficient preciseness of the approximation is balanced by a useful mathematical representation of Nu and r in the rational functions.

These formulas make it possible to do a relatively simple interpolation outside the free-molecule flow. Let us assume that with increasing density, the collisions of the molecules near the surface of the body disturb the free-molecule flow-by. This assumption is mathematically formulated by inserting into equations (9) and (10) the disturbing factor f, which represents the degree of braking for the molecules hitting the body. Let us assume that this braking is the same for each molecule. The magnitude of f is in the range $0 < f < 1$, and the reduced velocity of the molecules fC_0 is substituted in the

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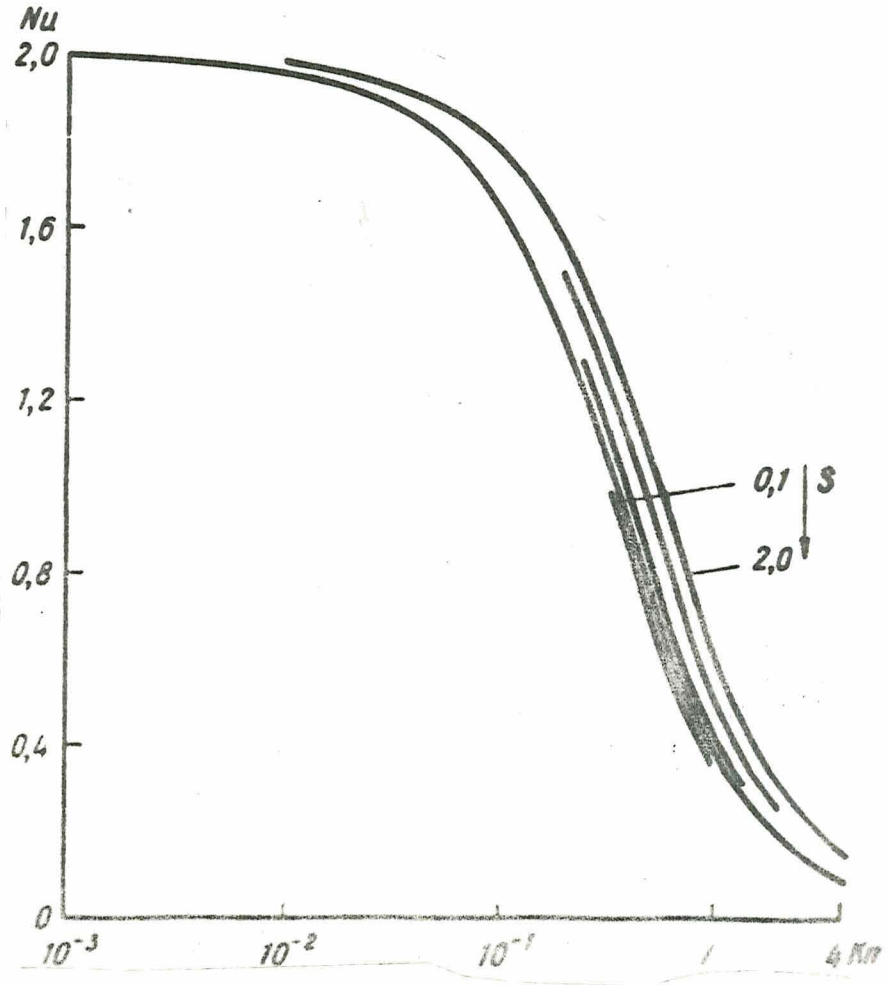
/1/

above formulas instead of C or instead of the molecular Mach number $\frac{S}{f}$. In this manner, equations (9) and (10) are generalized for the disturbed free-molecule flow. this range of flow is also frequently called the transitional flow. Together with slip flow, it forms the intermediate range between the continuum and free-molecule flow.

Formulas (9) and (10), transformed in the transition equations, are coupled with equations (4) and (5). We require that the parameters track smoothly in all ranges of flow. All this leads to an expansive system of algebraic equations, whose solution enables us not only to get the parameters NU and r, but also to determine the position of the boundaries of the flow ranges and the density-dependent curve of the new values: the slip factor m and the disturbing factor f.



Nusselt number as a function of Knudsen number

Figures 2 and 3 illustrate the results. Where Kn is the Knudsen number, the Nu number has a continuous value of 2 between Kn = 10^{-3} and Kn = 10^{-2}; at Kn = 10, it assumes the value of the free-molecule flow (Fig. 2). For the heat recovery factor (Fig. 3), corresponding

limiting values are reached at these numbers. Kn = 10^{-2} and Kn = 10 261/

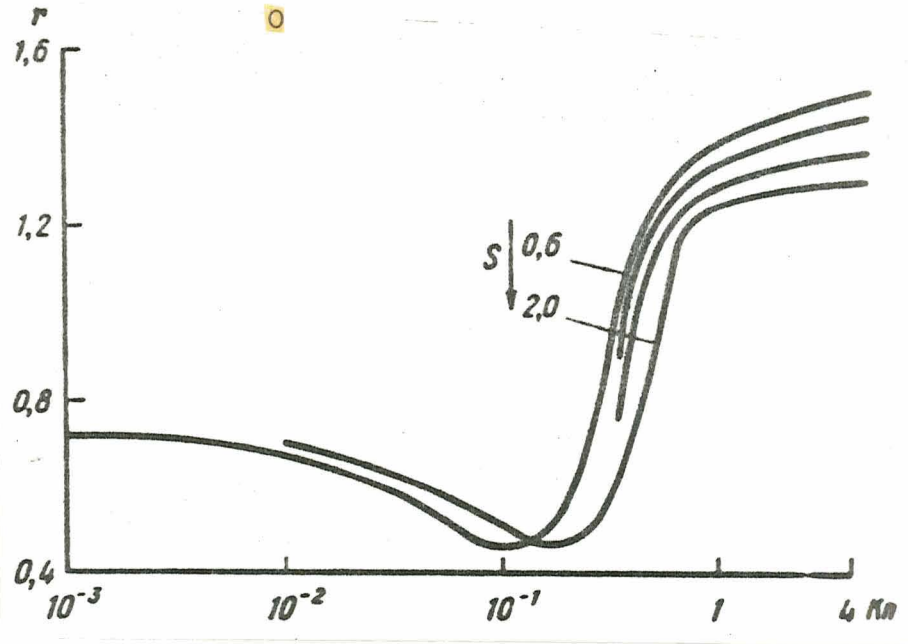


Figure 3. Temperature coefficient r as a function of the Knudsen number

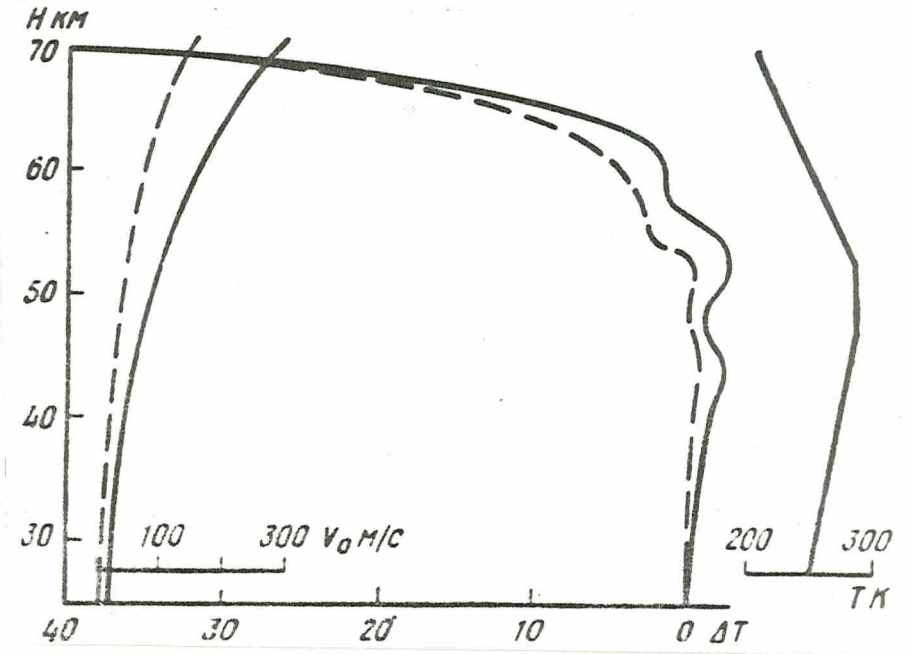


Figure 4. Error in temperature measurement with a bead thermistor, R = 0.25 mm, caused by heat transfer at two different velocity distributions with altitude

are known from the literature to be the boundaries of the continuum and free-molecule flow (references 4-6). In the heat recovery factor

and free-molecule flow (references 4-6). In the heat recovery factor curve (Fig. 3), the minimum in the middle part of the slip flow is readily apparent. This minimum also shows up in the results of the experimental research presented in references 5, 7, and 8.

As far as the boundary between slip flow and disturbed molecular flow go, there are values in the literature between Kn = 10^{-1} and 2 (references 4-6, 9, and 10). Our calculations point to a good match with these figures.

In summary, it can be said that we managed to find practical approximating formulas by a using physical interpolation for the intermediate flow. To work with the system of formulas, we developed a computer program, an example of whose use is presented in Figure 4. The figure presents the error in temperature measurement with a bead thermistor in rocket measurements based on inertia and dynamic heating.

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